High-strength greywater treatment in compact hybrid filter systems with alternative substrates

Kristjan Karabelnika, Margit Kõivac, Kuno Kasakd, Petter D. Jenssenb, Ülo Manderab,∗

a Department of Geography, Institute of Ecology and Earth Sciences, University of Tartu, 46 V anemuise St., Tartu 51014, Estonia
b Norwegian University of Life Sciences, Department ofMathematical Sciences and Technology, P.O. Box 5003, 1432 Ås, Norway

A R T I C L E   I N F O

Article history:
Received 4 May 2012
Received in revised form 13 July 2012
Accepted 10 August 2012
Available online 28 September 2012

Keywords:
Constructed wetlands
Hybrid filter systems
Filtralite
Greywater
Oil-shale ash

A B S T R A C T

Four parallel pilot-scale experimental filter systems were established in 2009 in order to study the treatment capacity of hydrated oil shale ash (an industrial by-product) and Filtralite® in compact highly loaded filter systems in order to reduce BOD and COD values and nutrient concentration in household greywater. The systems were tested at two different hydraulic loading rates over a nearly two-year period. All the Filtralite® systems performed significantly better than the oil shale ash system, showing a median COD reduction of 83–88%, whereas the system with 4–10 mm crushed Filtralite® performed significantly better than others filled with Filtralite®. The oil shale ash system clearly outperformed the Filtralite® system, with a median reduction of TP in the oil shale ash filter system of 89%, achieving a median effluent concentration of 0.55 mg P·L−1 compared to the respective 40–44% and 2.9–3.3 mg P·L−1 for Filtralite® systems. The median outflow pH values of the Filtralite® systems and oil shale ash system were ~8.5 and ~9, respectively. It was also noticeable that most of the organic matter, TSS and even TN and TP was removed in vertical flow(VF) filters. When operating the filter systems under ~2.5 times higher loading rates, there were no significant differences between the removal efficiencies regarding the organic matter, TSS and TN removal, although the fluctuations of pollutant content in inflow were more distinctly reflected in the outflow values and concentrations. The study serves as a good basis for the development of a low-tech compact filter system for greywater treatment.

© 2012 Elsevier B.V. All rights reserved.

1. Introduction

Water shortage has been recognized as one of the main problems in many countries (Li et al., 2010). In the developing world, insufficient water supply and poor sanitation facilities cause thousands of deaths each day, while in developed countries water wastage is often the norm and ineffective septic and wastewater treatment systems cause pollution of lakes, rivers and groundwater (Finley et al., 2009). Moreover, there are many remote unsewered areas that need to treat wastewater in challenging climatic and spatial conditions, as well as limited energy and water supply (Brisaud, 2007; Kadlec and Wallace, 2008).

Household wastewater is mainly divided into greywater and blackwater (Otterpohl et al., 1999; Palmquist and Hanaeus, 2005). Greywater is traditionally defined as wastewater that is produced in a household, and excludes toilet wastes (Liu et al., 2010). There is usually no separation between greywater and blackwater, so both streams are mixed and treated together (Gross et al., 2007). Since greywater is less contaminated than blackwater, purification of greywater is much faster and easier (Revitt et al., 2011). One option for the design of sustainable wastewater treatment systems involves the separate treatment of greywater in a combined filter system, although in order to develop a compact filter system, high loading rates need to be applied. Regarding the fact that compared to blackwater, greywater usually contains a minority of nutrients and more than 50% of organic matter from household wastewater, systems that can remove organic matter are needed in order to facilitate the discharge or reuse of the greywater (Li et al., 2009). Therefore the design of the system and the selection of filter materials are of crucial importance (Adam et al., 2007; Kõiv et al., 2010).

Greywater quantity varies accordingly from household, but it normally constitutes 50–80% of the total household wastewater (Eriksson et al., 2002; Li et al., 2009, 2010; Leal et al., 2007). It also depends on the development status of the countries in question: in developing countries the average production of greywater per capita is 20–30 L·d−1, whereas in developed countries it is as high as 90–120 L·d−1 (Li et al., 2009). There is also a high variation in greywater composition, which varies greatly depending on lifestyle

∗ Corresponding author. Tel.: +372 508 7373; fax: +372 737 5825.
E-mail addresses: kristjan@alkranel.ee (K. Karabelnik), margit.koiv@ut.ee (M. Kõiv), kuno.kasak@ut.ee (K. Kasak), petter.jenssen@umb.no (P.D. Jenssen), mander@ut.ee (U. Mander).

0925-8574/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.ecoleng.2012.08.035
characteristics such as family size, the age of the residents, their eating and washing habits and the detergents used for dishwashing and washing machines (Rasmussen et al., 1996; Eriksson et al., 2002).

Greywater normally includes wastewater from bathroom sinks, baths and showers, but also wastes from laundry facilities and dishwashers (Gross et al., 2007). Some authors exclude wastes from dishwashers and kitchen sinks because it is full of grease and food particles, and is therefore much more difficult to treat (Al-Jayyousi, 2003). In our research, kitchen and laundry wastewater is included.

There are many fields of application for the reuse of purified greywater, such as toilet flushing, garden/crop watering, irrigation, groundwater volume enlargement and the washing of roads and walls (Friedler and Hadari, 2006; Eriksson et al., 2009; Scheumann et al., 2008; Finley et al., 2009). If such reuse opportunities could be put into practice, a large quantity of fresh water could be saved.

The preceding investigations that have been carried out by other authors have revealed many different possibilities for greywater treatment (March and Gual, 2009; Abu Ghuwmi et al., 2010; Mourad et al., 2011). In this paper, constructed wetlands are considered as one option. Constructed wetlands (CW), especially subsurface flow filters (vertical and horizontal flow filters), are well suited to greywater treatment (Jenssen and Vrále, 2003). However, greywater has a great variation in loading rates and characteristics, so further research is required (Li et al., 2009).

Constructed wetlands have shown their ability to treat large amounts of wastewater using special filter materials (Jenssen and Vrále, 2003). In this study we analyzed different types of filter materials, such as industrial by-products (hydrated oil shale ash) and man-made products (Filtralite® and Filtralite-P®) in both vertical flow and horizontal flow subsurface filters. Vertical flow filters are suitable for oxygen-demanding processes such as nitrification, while horizontal flow filters are especially used for anaerobic processes. The main purification processes in horizontal flow filters are sorption, filtration and sedimentation (Vymazal et al., 1998).

Filtralite and Filtralite-P® are expanded light weight clay aggregates that are specially designed for wastewater treatment. Filtralite-P® is a modified filter material, and it has a high pH, Ca and Mg content (Jenssen and Krogsdal, 2003), so it is well-suited to phosphorus removal.

Oil shale is a kerogenous natural resource in Estonia, and it is used in Estonian thermal power plants. It is a solid fuel with a low energetic value, is highly calcareous (Vohla et al., 2005, 2011), and leaves large amounts of ash (45–48% of dry mass of shale). Recently Vohla et al. (2005) and Kaasik et al. (2008) have shown the great potential of Estonian Ca-rich hydrated ash sediment as a possible alternative filter material in CWs. Hydrated oil shale ash has great phosphorus-binding capacity. This is due to its high pH and high content of Ca-rich minerals, of which ettringite and portlandite are the most important (Kaasik et al., 2008; Liira et al., 2009).

The main objective of the study is to determine the treatment capacity of hydrated oil shale ash (an industrial by-product) and Filtralite-P® in compact highly loaded filter systems in order to reduce BOD and COD values and nutrient concentration in household greywater. The study was conducted as a part of the SANBOX project (www.sanbox.info) with the aim to develop a compact low-cost greywater treatment system.

2. Materials and methods

An onsite indoor experiment for the treatment of household greywater was in operation from October 2009 to July 2011. The study was carried out using greywater from a single household of five residents. The separated greywater piping system was built in order to collect wastewater from showers, hand basins, laundry and the kitchen.

2.1. Experimental system

The design and operating conditions of the greywater treatment experimental systems were chosen according to the technical requirements to the greywater treatment system to be developed during the SANBOX project. The system would treat greywater from 15–30 person equivalents with a hydraulic loading of 2.0–2.5 m³ day⁻¹, at that the system would be small enough to take space not more than 4 m² to fit in the international transport container. The study site conditions were also considered, that means the maximum amount of greywater for the tests was expected about 150–200 L day⁻¹. The layout and hydraulic regime (dosing frequency and distribution) was chosen according to the previous studies conducted in Norway (Rasmussen et al., 1996; Heistad et al., 2001).

The experimental pilot scale hybrid filter system (A, B, C and D; Fig. 1) consists of three shallow (h = 20 cm) parallel vertical flow filters (VF; 0.02 m³ each) followed by hydraulically saturated horizontal flow filters (HF; 0.06 m³ each).

The hydraulic loading rate of raw greywater was 32–80 L day⁻¹ (100–250 mm day⁻¹), with an additional re-circulation rate of 30%, which was found to be an optimal rate for the improvement of the aeration and overall purification efficiency of CWs (Pöldvere et al., 2009). For re-circulation, a re-circulation well (R, 0.07 m²; Fig. 1) was used.

Filter materials used in the systems were chosen as the typical ones used in compact filter systems in Norway and Estonia. The materials for the VF filter were expected to manage with high hydraulic loading, therefore having good hydraulic conductivity. The filter materials for the HF filter were mainly chosen on the basis of having a good P-sorption capacity. The filter materials are different fractions of Filtralite® in the VF of systems A, B and C (2–4 mm round, 4–10 mm crushed and 4–10 mm round respectively), Filtralite-P® in the HF of systems A, B and C in the fraction of 0–4 mm, and alkaline Ca-rich crushed/screened hydrated oil shale ash sediment (d = 5–20 mm) in the VF and HF of system D. Since the prototype of the greywater treatment system to be developed was expected to be used indoor conditions and the VF filters are placed on top of each other to minimize the required space, the systems were not planted.

Raw greywater was pre-treated in a settling tank (2 m³) and then led to the collection well (0.4 m³) in the test building. The pump in the collection well allocated equal parts of greywater to each system. Dosing of the pretreated greywater and recycled water from VF outflow was divided equally during the day. For example, if the hydraulic loading per system is 80 L day⁻¹ and the number of cycles is 40, 2.1 L of greywater is pumped onto the 3 parallel VF filters in after every 36 min. 300% of recycling was achieved by pumping the water from re-cycling well back to the VF filters three times between the greywater dosing, i.e. after every 12 min. Operational characteristics are described in Table 1.

2.2. Operational periods

The experiment was divided into two main periods based on the greywater loading rate applied to the systems. During the first period the loading rate was chosen to test four parallel systems in order to select two best performing pilot systems. The first period represents results from October 2009 to February 2010. In addition, results from 01.12.2009–22.12.2009 deviated from normal due to a technical problem: blackwater and greywater were accidentally mixed because of the high groundwater level in the
blackwater infiltration bed. The second period began in February 2010, when system C was switched off due to poor purification efficiency compared to the other Filtralite® systems. Thereafter, the total hydraulic loading rate was raised from 32.5 L d⁻¹ to 80 L d⁻¹ per parallel system (Table 1). During the second period from August 2010, the household began to use phosphorus-free detergents in order to determine the potential of phosphorus-free chemicals to reduce P loading in greywater. From April 2010 no further samples from system A were taken due to the non-satisfactory performance of the filter material, although the system was still running. Thus the data representing the results of the second period only comprise systems B and D. During the last period the unexpected failure of the test building’s heating system caused partial freezing of the filters, which somewhat affected the filters’ performance.

2.3. Sampling and data analysis

Water samples from a septic tank, a collection well and two sampling points – the outflow of the VF filters and the HF filter – of each parallel system were taken regularly. The raw greywater samples were collected from the primary settling tank. Samples from the test plant were taken from the collection well, the outflow from the vertical flow filters and the outflow from the horizontal flow filters, which also make up the system’s outflow. Five analyses were carried out on site: pH (also in the laboratory), temperature, oxygen concentration, dissolved oxygen and conductivity, which were all taken using a portable device (WTW Multi 350i). For the remaining parameters, samples were stored in a thermal box before being transported to the laboratory.

In the water samples, BOD₇, COD₇, total nitrogen (TN), NH₄-N, NO₃-N, NO₂-N, total phosphorus (TP), PO₄-P, SO₄²⁻ and pH were determined in a certified laboratory using standard methods (APHA-AWWA-WEF, 2005). A total of 14 and 13 samples were taken during the 1st and 2nd periods respectively.

This paper presents data and compares the purification efficiencies of different filter material and operational regimes in a pilot-scale hybrid filter system. For the comparison of purification efficiencies and outflow concentrations, BOD₇, COD₇, TSS, TN, and TP are used as performance indicators. The normality of the variables was verified using the Kolmogorov–Smirnov, Lilliefors and Shapiro–Wilk’s tests. Since the variables were not always normally distributed, non-parametric Mann–Whitney U-test and Wilcoxon Matched Pair tests were carried out in order to compare the performance of the filter systems during different operational periods and the performance of parallel filter systems during the same period respectively.

Table 1

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of parallel systems</td>
<td>-</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Total hydraulic loading rate per system</td>
<td>L d⁻¹</td>
<td>32.5</td>
<td>80</td>
</tr>
<tr>
<td>Hydraulic loading per VF filter*</td>
<td>mm d⁻¹</td>
<td>426</td>
<td>1048</td>
</tr>
<tr>
<td>Hydraulic loading per HF filter</td>
<td>mm d⁻¹</td>
<td>319</td>
<td>786</td>
</tr>
<tr>
<td>Hydraulic retention time in HF filter</td>
<td>h</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>Number of pumping cycles</td>
<td>cyc d⁻¹</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>Length of pumping cycle</td>
<td>s</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>Re-circulation rate</td>
<td>%</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Number of re-circulation cycles</td>
<td>cyc d⁻¹</td>
<td>60</td>
<td>120</td>
</tr>
<tr>
<td>Length of re-circulation cycle</td>
<td>s</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

* Including re-circulation.
3. Results

The median parameters of raw and pre-treated greywater did not differ significantly during the two test periods (Table 2). The median ratio between BOD:TN:TP in pre-treated greywater was 59:2.5:1 and 67:2.5:1 during Period 1 and Period 2 respectively.

3.1. Comparison of different filter materials

The filter systems and filter materials are compared on the basis of the results of the first period during which all of the systems were sampled (see Fig. 2).

The median reduction of the COD value was 83–88% for Filtralite® systems and 80% for the oil shale ash system, while the BOD7 value was on average reduced by 87–95% and 85% respectively. Regarding the reduction of COD value, all of the Filtralite® systems performed significantly better than the oil shale ash system, reaching median COD outflow values of 58–88 mg O2 L−1 for Filtralite® and 105 mg O2 L−1 for oil shale ash systems. However, the respective median values for BOD7 were 20–43 mg O2 L−1 and 38 mg O2 L−1, indicating no significant difference between system C and system D for the reduction of BOD7 value.

Among the Filtralite® systems, system B (VF with 4–10 mm crushed Filtralite®) performed significantly better than other Filtralite® systems (A and C) regarding organic matter and TSS removal. However, there were no significant differences between Filtralite® systems A and C.

Table 2
Median parameters (±StDev) of raw and pre-treated greywater during the test periods.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Period 1</th>
<th>Period 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Raw greywater</td>
<td>Pre-treated greywater</td>
</tr>
<tr>
<td>pH</td>
<td>–</td>
<td>6.8 ± 0.2</td>
<td>7.0 ± 0.2</td>
</tr>
<tr>
<td>TSS</td>
<td>mg L−1</td>
<td>155 ± 26</td>
<td>130 ± 14</td>
</tr>
<tr>
<td>BOD7</td>
<td>mg O2 L−1</td>
<td>385 ± 72</td>
<td>300 ± 77</td>
</tr>
<tr>
<td>CODCr</td>
<td>mg O2 L−1</td>
<td>640 ± 135</td>
<td>530 ± 87</td>
</tr>
<tr>
<td>TN</td>
<td>mg O2 L−1</td>
<td>13.0 ± 2.6</td>
<td>12.5 ± 3.2</td>
</tr>
<tr>
<td>NH4-N</td>
<td>mg N L−1</td>
<td>1.9 ± 1.4</td>
<td>2.8 ± 1.9</td>
</tr>
<tr>
<td>NO3-N</td>
<td>mg N L−1</td>
<td>0.02 ± 0.005</td>
<td>0.02 ± 0.003</td>
</tr>
<tr>
<td>TP</td>
<td>mg P L−1</td>
<td>6.8 ± 2.7</td>
<td>5.1 ± 1.4</td>
</tr>
<tr>
<td>PO4-P</td>
<td>mg P L−1</td>
<td>3.9 ± 1.19</td>
<td>3.9 ± 0.79</td>
</tr>
</tbody>
</table>

Fig. 2. Outflow values of COD, and concentrations of TSS, TN and TP of four parallel filter systems during Period 1. The letters A, B, C and D indicate the symbol of a parallel system. The VF and HF show the outflow value or concentration of the VF filter and parallel filter system respectively. Letters with an asterisk (*) above the bars indicates differences between respective values or outflow concentrations of parallel filter systems: * at p level <0.05 and ** at p level <0.01. Inflow and outflow parameters differed significantly (p <0.01) in all cases.
The removal efficiency of TN was moderate, and the median efficiency of Filtralite® systems and the oil shale ash system were 47–55% and 46% respectively. Nevertheless, a median outflow concentration of 6.0–6.8 mg N L⁻¹ was achieved. Still, there were no significant differences in TN removal between different Filtralite® systems and between Filtralite® and oil shale ash systems.

The results of TP removal showed that the median reduction of TP in the ash filter system was 89%, achieving a median effluent concentration of 0.55 mg L⁻¹ compared to the respective 40–44% and 2.9–3.3 mg PL⁻¹ for Filtralite® systems. Whereas the same filter material (Filtralite-P®) was used in the HF systems of all the Filtralite® systems, no significant differences were observed between the different Filtralite® systems.

Surprisingly, the results show that most of the organic matter, TSS, and even TN and TP, was removed in the VF filters, while the HF filters showed minor or sometimes even negative removal efficiencies. The median overall contribution of the reduction of COD value of the HF filters was 1.3%, while the HF of system B had no effect whatsoever on COD reduction performance.

### 3.2. The effect of loading rate on performance

During Period 2, when two filter systems, B (Filtralite®-based) and D (oil shale ash-based), were tested under ~2.5 times higher loading rates, the systems performed similarly to Period 1 (see Fig. 3). The median COD removal of system B remained at 88%, while the respective number for system D decreased from 80% to 76%. The removal of BOD₇ in both systems was only slightly better during Period 1: for system B 95% and 92% respectively, and for system D 85% and 78% respectively. Regarding organic matter, TSS and TN removal, however, there were no significant differences between the two periods.

Nevertheless, the TSS removal of the VF filters decreased significantly. The median removal of TSS in the VF of system B was 90% in Period 1 compared to 86% in Period 2, and the respective outflow values were 13 mg L⁻¹ and 19 mg L⁻¹. The respective values for system D were 80% and 66%, and 27 mg L⁻¹ and 54 mg L⁻¹. While the results show that most of the organic matter, TSS and even TN and TP was removed in the VF filters during the lower loading rate conditions, in the higher loading rate conditions the contribution of HF in the overall performance of filter systems increased. The median overall contribution of the reduction of the COD value of the HF filters of system B and D was 3.7% compared to the 1.4% during Period 2. The respective numbers for the reduction of TSS concentration were 2.4% compared to 7.5%.

### 3.3. Dynamics of pollutant removal

The dynamics of pollutant removal are presented for systems B and D, which were both sampled throughout the entire experiment (see Figs. 4 and 5).

The median outflow pH values of the VF filters were 8.1–8.2 for the Period 1, dropping to 7.8–7.9 for the Period 2 (system B and D) for all of the filters. The respective values for the HF filters were 8.4–8.6 for Filtralite® systems (A, B, C) and 9.2 for oil shale ash
**Fig. 4.** Dynamics of COD, BOD\(_7\), TSS and TN removal in filter systems B (4–10 mm crushed Filtralite\®) and D (hydrated oil shale ash). VF–vertical flow filter outflow, HF–horizontal flow filter outflow. The dashed vertical line represents the end of the first period. The X axis shows the time (in days) from the beginning of the experiment.

**Fig. 5.** Dynamics of total phosphorus (TP) removal in filter systems B (4–10 mm crushed Filtralite\®) and D (hydrated oil shale ash). VF–vertical flow filter outflow, HF–horizontal flow filter outflow. The dashed vertical line represents the end of the first period, and the dotted vertical line indicates the beginning of the use of phosphorus-free chemicals.

It can be seen from Fig. 4 that TN removal during Period 1 was affected by the failure of the system, which led to the temporary inflow of diluted blackwater into the experimental system and significantly raised the median TN outflow concentrations of both filter systems. The effect of the failure on the performance of the systems in other outflow parameters appears to be irrelevant.

Regarding the oil shale ash, the results indicate that under cold water temperature (median 8 °C) and high pH (median outflow value for the Period was 9.2) conditions, the filter system needs a longer starting period to develop a microbial community for biological processes. It appears that it takes around 50–70 days from the beginning of the experiment to establish a microbial community and get stable outflow values for systems B and D.

Although there were no significant differences between the two periods regarding organic matter, TSS and TN removal, the dynamics of pollutant removal indicates that due to the higher hydraulic loading rate in Period 2, the greywater-typical fluctuations of pollutant content in inflow (Eriksson et al., 2009) are more distinctly reflected in the outflow values and concentrations. The highest peak in the outflow values and the concentrations of all pollutants was caused by the unexpected failure of the heating system of the test building during the last period, which caused partial freezing of the filters. Nevertheless, it can be observed that in some cases the fluctuations in inflow concentrations together with a high
hydraulic loading rate can lead to washout of finer particles, which was the case of the higher median TSS concentrations in the outflow of the VFB filter during Period 2.

Regarding TP removal, the Filtralite® and oil shale ash system showed distinctively different dynamics (see Fig. 5). During Period 2, when the hydraulic loading rate and TP concentration increased considerably, the outflow concentration of the Filtralite® system increased significantly (up to 9.1 mg L⁻¹), although the outflow concentration of the oil shale ash system still was fairly stable (up to 2.1 mg L⁻¹).

During the Period 2, since the household began to use phosphorus-free detergents, the TP concentration in the raw and pretreated greywater fell to median values of 2.6 and 1.5 mg L⁻¹ respectively. Concurrently, the median outflow concentration of the Filtralite® system fell to 1.2 mg L⁻¹, while the median outflow concentration for the oil shale ash system showed only a slight decrease and fell to 1.6 mg L⁻¹.

4. Discussion

The composition of raw greywater in our study corresponds to the typical values for mixed greywater (Li et al., 2009), and according to the suggested BOD₃:COD ratio (~0.5) shows good biodegradability. In addition, the raw greywater had a nearly balanced COD:N:P ratio, as suggested by Tchobanoglous and Burton (1991).

We achieved good results regarding the removal of BOD, COD and TSS in highly loaded filter systems treating mixed greywater. The median BOD₃ removal of Filtralite® systems was up to 92% at a organic loading rate of 90.7 g O₂ m⁻² d⁻¹ and a hydraulic loading rate of 1048 mm m⁻² d⁻¹. There are, however, only a few studies of similar filter systems that have been conducted with greywater under high hydraulic and pollutant loading rates. In using such filter systems, it is common for either high hydraulic loading rates to be applied using low-strength greywater (Kadewa et al., 2010) or for lower hydraulic loading rates to be applied using medium-strength greywater (Paulo et al., 2009). There are, however, several studies conducted in Norway analyzing the potential and different applications of Filtralite® as a filter medium for constructed wetlands and filter systems under various hydraulic and pollutant loading rates (Rasmussen et al., 1996; Heistad et al., 2001; Jenssen et al., 2005).

4.1. Design considerations of filter systems

In applying high loading rates, the design considerations of filter system play a very important role in achieving optimal performance (filter depth, dosing rates and frequency, grain size of filter media, distribution system). The fact that even shallow filters can show excellent BOD removal has been demonstrated in this study and has previously been reported by several authors (Rasmussen et al., 1996; Kadewa et al., 2010). Rasmussen et al. (1996) studied the effect of filter depth on the removal of BOD and bacteria in Filtralite® filters and concluded that BOD removal was independent of filter depth for filters with heights of between 20 and 60 cm, but bacteria removal was lower for the shallow filter depth. If we consider that in our study the 60 cm thick layer was divided into three 20-cm layers of parallel VF filters, the hydraulic and pollutant loading is three times higher than the comparable 60-cm-high filter that is common for VF filters.

Another design issue is the distribution and dosing system, which has to allow the even distribution of water onto the filter surface and to apply individual loading rates and dosing frequencies in order to improve the systems’ performance in conditions of high hydraulic loading. This even distribution maximizes the retention time at a given loading rate and assures that the entire volume of the filter is used efficiently for purification processes.

In our experiment we used the same spray nozzles as those reported by Heistad et al. (2001), but the pumps ensured the head at nozzles between 3 and 5 m, compared to the 10–20 m suggested by Heistad et al. (2001). The higher pressure produces finer water particles, thereby enhancing oxygenation and ensuring more even distribution, which would probably result in the better utilization of filter material and improved performance of the filter system in BOD, COD and TSS removal. Therefore the performance of the filter system would likely have been even better when using pumps with a higher pressure head at the nozzles.

Regarding organic matter and TSS removal, all Filtralite® systems performed significantly better than the oil shale ash system. This is most likely due to the finer particle size of the Filtralite® filters, which ensures better removal efficiencies as a result of its larger specific area (Rasmussen et al., 1996). This also explains the better performance of VF filters using 4–10 mm crushed Filtralite® than the systems that used Filtralite fraction with 4–10 mm round particles. However, unlike the data reported by Jenssen and Vråle (2003) when applying higher hydraulic loading rates, the finer material tends to clog, as was observed in the VF filters filled with Filtralite® 2–4 mm during Period 2. The other explanation for clogging is the additional hydraulic loading from re-circulation together with high organic loading, which caused the rapid growth of biofilm on the surface of the filter material.

The results show that most of the organic matter, TSS and even TN and TP was removed in the VF filters. Regarding organic matter removal, this is concurrent with the study reported by Heistad et al. (2006), where a BOD removal of 96% was achieved in a single-pass aerobic pre-treatment filter and indicates that in cases where there is no need for TP removal or in areas where phosphorus-free detergents are used, the filter system can be designed based only on VF filter(s). The application of phosphorus-free chemicals in households can reduce TP concentration below 1 mg P L⁻¹ in septic tank effluent (Jenssen and Vråle, 2003). However, microbial contamination should be taken into consideration in such cases.

4.2. Phosphorus removal

The excellent TP removal of the oil shale ash filter was in close accordance to previous studies and was mostly based on active filtration by forming of Ca-phosphate (Liira et al., 2009; Köiv et al., 2010). Unlike Liira et al. (2009), however, who reported a decrease from 91% to 49% in TP removal over a five-month period at a loading of 1.66 g P m⁻² d⁻¹ and a residence time of 18 h, in our experiment the TP removal efficiency remained high (87%), although the loading of TP at the beginning of Period 2 (before the use of phosphorus-free detergents) was 5 times higher, 0.57 g P m⁻² d⁻¹ and 2.93 g P m⁻² d⁻¹ respectively at a residence time of 6 h in the HF filter. Nevertheless, the outflow values of TP increased during Period 2, and the TP removal efficiency of the VF filters dropped from a median value of 81% in Period 1 to a median value of 39% at the beginning of Period 2, indicating the negative effect of high hydraulic loading over a short retention time.

Contrarily, the fairly poor performance of Filtralite-P® in TP removal was not expected on the basis of the results reported by Jenssen et al. (2005) and Heistad et al. (2006) for the Filtralite-P® systems tested in Norway. One possible explanation for this is the low pH value of the outflow of Filtralite-P® systems. In our experiment the intial pH values of the outflow of HF filters
Filtralite® systems was around 9.0, dropping and stabilizing around 8–8.5 within two months from the beginning of the experiment. Adam et al. (2007) reported that the effluent pH of the column experiment was initially above 10.5, dropping to between 9 and 9.5 over 303 days, while an overall P removal rate of 91% was measured for the Filtralite-P® treating the secondary wastewater. Whereas the removal of P in Filtralite-P® filters is based on the sorption process that is induced when pH is higher than 8 (Adam et al., 2007), the effect of pH on P removal is likely. One reason for the low pH may be the buffering effect of CaCO₃ system in the influent greywater which prevented the pH rise above 9.

The high loading rates applied to the filter systems allow these to be used in places where space is limited, in areas that are far from central sewage systems or where there is a lack of potable water. Moreover, the occasional sampling of the filter systems for microbial contamination during the first months of operation showed that the effluent quality of all of the filter systems was far below the normative values for the quality of EU bathing water. Thus the effluent can be reused for toilet flushing or irrigation. Based on this study, the preferred filter material for the VF filter could be crushed Filtralite® fraction of 4–10 mm, while for the HF filter the suggested material would be hydrated oil shale ash sediment. However, the improvements of the filter system regarding pumping pressure and distribution system should also be considered before designing a prototype. Based on previous studies the expected lifespan of compact filter systems with oil shale ash would be longer than two years (Liira et al., 2009). In case of Filtralite-P systems, previous studies have shown excellent P-removal of highly loaded filters more than five years (Heistad et al., 2006). Once saturated with P, the filter materials are potentially useful for soil amendments (Kölv et al., 2012; Kvvarnström et al., 2004). If lower pH of the effluent is required for re-use purposes, an extra peat-filter filled with highly decomposed peat can be used, to reduce pH down to 7–8 (Liira et al., 2009).

5. Conclusions

The highly loaded filter systems for greywater treatment demonstrated good performance in COD, BOD, TSS and TP removal. The results provide encouragement for the application of similar full-scale systems in places where space for the establishment of CWs is limited, in areas that are far from central sewage systems and/or where there is a lack of potable water. The system’s effluent can be reused for toilet flushing or irrigation. In hybrid filters, the preferred filter material for the VF filter could be crushed Filtralite® fraction of 4–10 mm, while for the HF filter the suggested material would be hydrated oil shale ash sediment. However, the improvements of the filter system regarding pumping pressure and distribution system should also be considered before designing a prototype. The feasibility of the full-scale system depends on local conditions such as the availability of fresh water, electric supply, also the requirements for the effluent. The application of proposed system is probably feasible solution for remote places with low space, limited fresh water and electrical supply and far from public sewerage.

Acknowledgements

The study was conducted in a research project supported by the 7th EU Framework project No 232274 “SANBOX – Development of an innovative sanitation and wastewater treatment system for remotely located tourist facilities”. Financial support was also provided by Target Funding Project No. SF0180127T08 of the Ministry of Education and Science of Estonia.

References


